THE NEUPERT EFFECT AND NEW RHESSI MEASURES OF THE TOTAL ENERGY IN ELECTRONS ACCELERATED IN SOLAR FLARES

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ABSTRACT

It is believed that a large fraction of the total energy released in a solar flare goes initially into accelerated electrons. These electrons generate the observed hard X-ray bremsstrahlung as they lose most of their energy by coulomb collisions in the lower corona and chromosphere. Results from the Solar Maximum Mission showed that there may be even more energy in accelerated electrons with energies above 25 keV than in the soft X-ray emitting thermal plasma. If this is the case, it is difficult to understand why the Neupert Effect – the empirical result that for many flares the time integral of the hard X-ray emission closely matches the temporal variation of the soft X-ray emission – is not more clearly observed in many flares. From recent studies, it appears that the fraction of the released energy going into accelerated electrons is lower, on average, for smaller flares than for larger flares. Also, from relative timing differences, about 25% of all flares are inconsistent with the Neupert Effect. The Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) is uniquely capable of investigating the Neupert Effect since it covers soft X-rays down to 3 keV (when both attenuators are out of the field of view) and hard X-rays with keV energy resolution, arcsecond-class angular resolution, and sub-second time resolution. When combined with the anticipated observations from the Soft X-ray Imager on the next GOES satellite, these observations will provide us with the ability to track the Neupert Effect in space and time and learn more about the relation between plasma heating and particle acceleration. The early results from RHESSI show that the electron spectrum extends down to as low as 10 keV in many flares, thus increasing the total energy estimates of the accelerated electrons by an order of magnitude or more compared with the SMM values. This combined with the possible effects of filling factors smaller than unity for the soft X-ray plasma suggest that there is significantly more energy in nonthermal electrons than in the soft X-ray emitting plasma in many flares.

INTRODUCTION

For over 25 years, since the work of Lin and Hudson (1976), we have known that a large fraction of the total energy released in a solar flare goes initially into accelerated electrons. They analyzed the multiwavelength observations of four large flares that occurred in August 1972 and found that "the >20 keV electrons contain 10 to 50% of the total energy output" of these flares. Indeed, if the electron energy spectrum extended down to 5 – 10 keV with the same power-law index as that observed above 20 keV, then the electrons would provide all the energy for the flare explosions. This precision must be contrasted with the outcome of the study of flare energetics conducted at the SMM workshops, where it was found that not a single component of the energy budget "is presently known to better than an order of magnitude" (Hudson 1986). In view of this difficulty in determining the energetic contributions of the different components of the flare energy budget for any given flare, we have adopted another approach to determining the importance of accelerated electrons based on the Neupert Effect since it could be expected to be clearly seen if the electrons carried most of the energy.

The canonical model of solar flares has energy released impulsively from the coronal magnetic field to accelerate electrons to >10 keV and ions to >10 MeV. The total energy in accelerated electrons is found to be similar to that in accelerated ions, at least in the largest, gamma-ray flares (Ramaty et al., 1995), but this contribution will not be considered further in this paper. The energized electrons lose most of their energy in coulomb collisions in the ambient plasma with only $\sim 10^{-5}$ of their energy producing the observed electron-ion bremsstrahlung X-rays. They also generate synchrotron radio emission as they spiral about the coronal magnetic field lines. The protons and heavier ions produce gamma-rays of characteristic energies through nuclear interactions with the ions of the ambient plasma. In addition to particle acceleration during the flare, plasma is heated to $>10^7$ K. It produces thermal bremsstrahlung soft X-ray emission and subsequently cools by radiation and conduction.

Neupert (1969) noticed that for many flares, the time integrated microwave and hard X-ray fluxes "closely match the rising portions of the soft X-ray emission curves." This implies that the same energetic electrons that produce the observed hard X-ray and microwave emissions also heat the plasma that produces the soft X-ray emission. As pointed out by Dennis and Zarro (1993), the Neupert Effect must exist for virtually any flare model if the hard X-rays are electron-ion bremsstrahlung and the plasma cooling time is long compared to the characteristic durations of the impulsive hard X-ray or microwave peaks. Thus, by examining the Neupert effect, it should be possible to determine what fraction of the plasma heating results from the accelerated electrons and what fraction comes from some other agent such as direct plasma heating in the energy release process itself.

Lee et al. (1995) point out that the correct way to interpret the Neupert Effect is to equate the total time-integrated energy deposited by the accelerated electrons ($\in_e$) and the maximum thermal energy of the heated plasma ($\in_{th,\,max}$), i.e., $\in_e = \in_{th,\,max}$

Unfortunately, it is difficult to calculate either of these two energies to better than an order of magnitude from the observed soft and hard X-ray emissions. The total energy in accelerated electrons is uncertain, even assuming thick-target interactions, primarily because of our lack of knowledge of the lower energy cutoff to the assumed power-law electron spectrum. The thermal energy of the heated plasma is uncertain primarily due to the lack of knowledge of the volume, filling factor, and density of the emitting plasma. In addition, the soft X-rays only provide information about the hotter plasma with temperatures above a few million K. Observations at other wavelengths are needed to provide information on lower temperature material.

Lee et al. (1995) have shown that there must be a systematic deviation from the Neupert Effect as a function of total flare intensity based on the different soft and hard X-ray flare size distributions. Soft X-ray flares have a power-law size distribution of peak fluxes with a slope of ~1.8 whereas hard X-ray flares have a power-law distribution of fluences with a slope of ~1.6. They speculate that another form of plasma heating must be present in addition to accelerated electrons in order to explain this discrepancy.

Veronig et al. (2002) also suggest that there must be another form of plasma heating to explain their results. They showed that the average ratio of the GOES SXR peak flux and the HXR fluence measured with CGRO/BATSE is larger for smaller flares (as determined from either the SXR or HXR emissions). They speculate that the additional heating mechanism is proportionally greater for smaller flares. This is in agreement with the requirement found by Lee et al. (1995) to explain the difference in SXR and HXR flare size distributions.

With the RHESSI imaging observations covering both the hard and soft X-ray range (down to ~3 keV when the shutters are out of the field of view), we can now look for the Neupert effect on a spatial as well as temporal basis. It should be possible to test the thick-target interpretation of the Neupert effect and to determine where any additional plasma heating is taking place in the flaring region. Furthermore, we can measure the ratio of SXR flux to HXR fluence as the flare progresses and determine the required contribution of any additional heating agent as a function of time.

Thermal vs. Nonthermal Energetics

If we restrict ourselves to comparing the energy in accelerated electrons with the energy in the hot thermal plasma that produces the soft X-rays, there are several examples in the literature for many different flares. Over 30 flares were studied for the SMM workshop chapter on Flare Energetics of the Impulsive Phase (de Jager et al. 1986). The energy in electrons >25 keV was estimated from the Hard X-ray Burst Spectrometer (HXRBS)

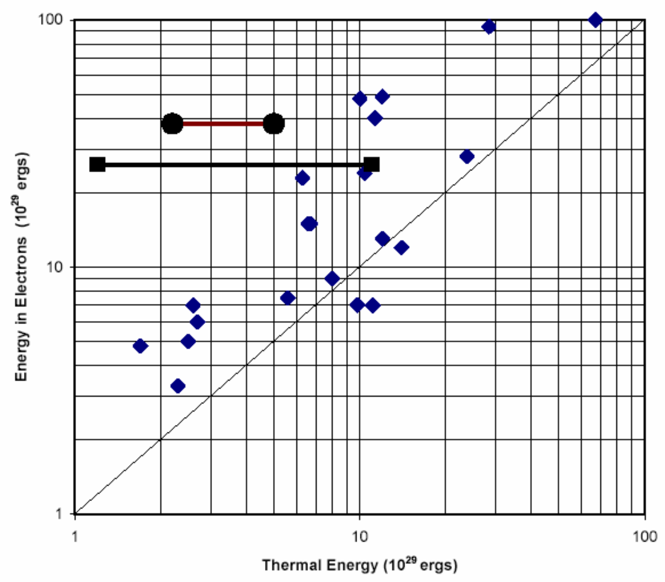

Figure 1. Diamonds show the energy in electrons >25 keV determined from HXRBS hard X-ray observations vs. energy in thermal plasma determined from the HXIS soft X-ray observations for flares seen with SMM in 1980 (from de Jager, 1986). The squares and circle are for RHESSI flares seen with the energy in electrons for energies >10 keV. The squares are for a flare observed on 26 February 2002, where the left hand point is for the footpoints and the right hand point is the ejecta (Saint-Hilaire and Benz, 2002). Solid circles are for the RHESSI flare on 20 Feb. 2002 (see text).

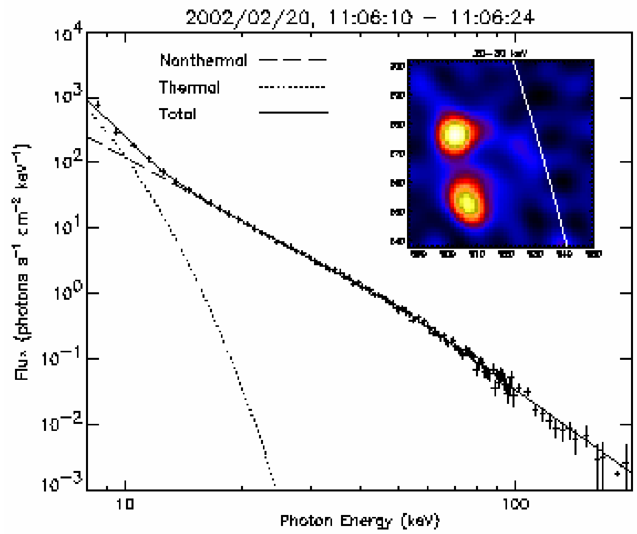

Figure 1. X-ray image and spectrum measured with RHESSI for the flare observed on 20 Feb. 2002 at 11:06 UT (Sui et al. 2002). The spatially integrated spectrum is for the 14-s interval during the impulsive hard X-ray peak. The nonthermal fit is a broken power-law with a slope of -3.3 below and -4.3 above 52 keV. The thermal-bremsstrahlung component is for a temperature of 16 MK and an emission measure of 1.8×10^{48} cm^{-3}. The inset shows the image in the 20 – 30 keV range with 7-arcsecond resolution. The white line shows the location of the solar limb.

observations by integrated the electron flux, calculated assuming thick-target interactions, over the duration of the flare, the energy in the hot thermal plasma was estimated from the Hard X-ray Imaging Spectrometer (HXIS) observations (3 – 30 keV) at the time of the peak soft X-ray emission.

The comparison in Figure 1 shows an embarrassingly large amount of energy in electrons compared to the energy in the hot thermal plasma. For most flares there is considerably more energy in the electrons than in the thermal plasma. The thermal energy was broken down into two components, the "kernel" and the "tongue." The "kernel" source was close to the footpoints seen in hard X-rays while the "tongue" was presumably from plasma extending into the corona. The energy in electrons >25keV is up to a factor of ~40 greater than the thermal energy in the kernel. If the total thermal energy in the kernel plus the tongue is considered then the ratio of thermal to nonthermal energy is closer to unity. However, two uncertainties in these measurements suggest that there is, in fact, more energy in nonthermal particles than in the thermal plasma. Firstly, the energy in electrons could be considerably higher than that shown in Figure 1 if the electron spectrum extends below 25 keV. This energy was originally set more by the lower energy threshold of the scintillation hard X-ray spectrometers of the day than by the requirements of any solar flare model. Secondly, the thermal energy could be considerably less than that indicated in Figure 1 if the filling-factor is less than one (the thermal energy depends on the square-root of the filling factor).

There have been suggestions since hard X-rays were first detected from flares that the nonthermal spectrum extends down to well below 25 keV. Kane and Anderson (1970) obtained a power-law spectrum for several flares down to 10 keV. Kahler and Kreplin (1970) report three events in which the impulsive component, presumed to be nonthermal, extended down to the 3 – 10 keV energy range.

There are now several reported RHESSI observations where it can be shown that the electron spectrum probably extends down to 10 keV rather than the 25 keV that was assumed for the SMM flares. One example from Sui et al. (2002) is shown in Figure 1, where the spatially-integrated spectrum at the time of the impulsive hard X-ray peak in the flare observed with RHESSI on 20 February 2002 at 11:06 UT is plotted. The inset image shows that the 20 to 30 keV X-rays come from two bright patches, probably loop footpoints consistent with the nonthermal thick-target model. The power-law spectrum with a slope of -3.3 extends down to close to 10 keV before it becomes dominated by the steeper thermal spectrum. Assuming thick-target interactions, then the electron spectrum would have a slope of -4.3 and the energy in electrons above 10 keV is 4 x 10^{30} ergs. For comparison with the SMM results, this is a factor of $(25/10)^{3.3} \approx 20$ greater than the energy in electrons above 25 keV. The thermal energy in the soft X-ray emitting plasma is calculated assuming unity filling factor from the thermal fit to the spectrum taken at the time of the peak in the 6 – 12 keV channel. The temperature determined from the fitted spectrum at this time is 25 MK and the emission measure is 4.2×10^{47} cm^{-3}. The volume of 1.9 x 10^{27} cm^3 was determined from the image made for the same time interval using the area inside the 50% contour raised to the power of 1.5. These parameters give a total thermal energy at the time of the peak in soft X-rays to be 2 x 10^{29} ergs or a factor of 20 smaller than the energy in electrons above 10 keV. This is plotted as the left hand circle in Figure 1. The temperature and emission measure derived from GOES at the same time are 15 MK and 6 x 10^{48} cm^{-3}, respectively, which, assuming the same volume, gives a total thermal energy of 5 x 10^{29} ergs or a factor of 8 smaller than the energy in electrons above 10 keV. This is plotted as the right hand circle in Figure 1. The difference between the energies calculated from the RHESSI and GOES observations may result from the higher energies covered with RHESSI since the thin shutters were in the field of view for this observation. It could also suggest that there may be more thermal energy at even lower temperatures than those covered with GOES. Nevertheless, we can say that for this flare, there is about an order of magnitude difference between the high-temperature thermal and the nonthermal energies.

It is not clear what causes the steepening of the spectrum at energies above ~50 keV seen in Figure 1. Breaks at similar energies have been observed before (Lin and Schwartz, 1987) and are often seen in RHESSI flare spectra (Saint-Hilaire and Benz, 2002). There origin is not clear but they are almost certainly not instrumental. The simplest explanation is that they are the result of a steepening in the electron spectrum at high energies as the result of the acceleration process. In any case, they do not significantly affect the energy budget since most of the energy in electrons resides at lower energies.

The Neupert Effect

If the energy in the accelerated electrons is indeed such a large fraction of the total energy released in a flare, then one would expect that the Neupert Effect would show up very clearly. We show just one example taken from the RHESSI observations of the first X-flare it observed on April 21, 2002, starting at 00:40 UT. The 25 – 50 keV time profile is shown in Figure 3 along with the timed derivative of the GOES 1 – 8 Å flux. The general agreement between these two curves can be readily seen although there is no detailed correlation. Of particular interest is the time interval spanning the highest hard X-ray peak between 01:15 and 01:17 UT. This peak is shown on an expanded time scale in Figure 4 along with the corresponding soft X-ray time derivative. A clear correlation can be seen in three peaks although the relative amplitudes are much different in the two curves. It must be kept in mind that the plotted soft X-ray time derivative was obtained by first smoothing the 3-s GOES-10 observations with an

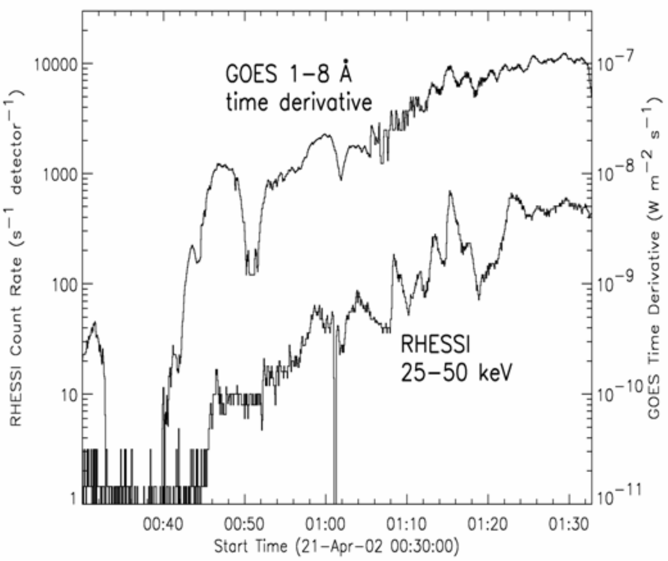

Figure 3. Plot of RHESSI 25 – 50 keV flux (bottom curve) and the time derivative of the smoothed GOES 1 – 8 Å intensity (top curve) vs. time for the rise phase of the 21 April 2002 X1.5 flare.

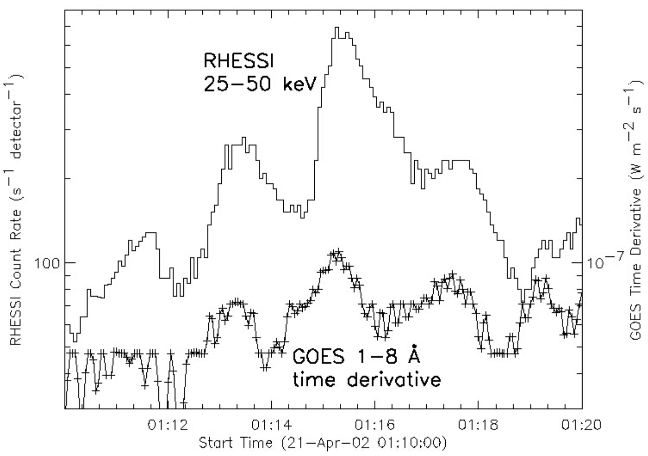

Figure 4. Expanded plot of time interval showing major peak in the hard X-ray time profile (upper curve) and the corresponding peak in the time derivative of the GOES soft X-ray time profile (lower curve). The 3-s GOES data were first smoothed with an 11-point boxcar function before taking the first differences to obtain the indicated curve. The saw-tooth appearance results from the digitization levels in the original data.

11-point boxcar filter before taking the first differences. Thus, the plotted points are not independent and the peaks appear more significant than they are. Nevertheless, at least the central peak at ~01:15 UT seems to be significant above the noise and digitization level. Furthermore, it shows up with similar amplitude in plots determined from both GOES-8 and GOES-10 observations. It is significant that the subsequent hard X-ray peak at 01:23 UT does not show any equivalent counterpart in the soft X-ray time derivative plot.

Conclusions

We have seen that for many solar flares, the total energy in accelerated electrons is calculated to be at least equal to the peak energy in the hot plasma if not an order of magnitude or more higher. This was found to be true even with the SMM observations where the spectrum of the accelerated electrons was assumed to be cut off at 25 keV. Now, using the new RHESSI observations with much higher spectral resolution and going down to as low as 3 keV, it is clear that the power-law photon spectrum extends down to as low as 10 keV in many flares before it becomes dominated by a more steeply falling and presumably thermal spectrum. Thus, the total energy in the accelerated electrons must be about an order of magnitude higher than estimated using the SMM observations, depending on the steepness of the power-law spectrum.

Where does all of the energy in electrons go if it does not immediately heat the plasma and show up as thermal energy of the soft X-ray emitting plasma? It is well known that a significant amount of energy appears as mass motion, both turbulent and directed. This was revealed from the line broadening and blue-shifted line components seen in soft X-ray and EUV lines with such instruments as the Bent Crystal Spectrometers (BCS) on both SMM and Yohkoh. We do not currently have any such comprehensive measure of this mass motion although the RESIK instrument on the Russian CORONAS-F spacecraft launched on 24 May 2001 has a version of BCS on board providing this information (Sylwester et al. 2002).

But why is the Neupert Effect not seen more clearly and only for some of the hard X-ray peaks but not others? One approach we can now take given RHESSI's high spatial resolution as fine as 2.3 arcsecond at energies up to 100 keV is to search for what can be called the spatial Neupert Effect. The detailed time history of the footpoint emissions can be examined in detail to determine if the direct heating can be seen as the electron beam enters the high density regions. Early indications that this would be a powerful diagnostic tool to test this simple flare picture were obtained from Yohkoh observations (McTiernan et al. 1993, Hudson et al. 1994). They used the Hard X-ray Telescope (HXT) to image the nonthermal hard X-rays and the Soft X-ray Telescope (SXT) to image the heated plasma. Surprisingly, they found for two flares that one footpoint showed an impulsive peak in both the hard and soft X-ray emissions from the same location. The rapid rise in both fluxes was interpreted as resulting from the initial rapid heating of the plasma as the electron beam entered the footpoint. The near simultaneous fall in both fluxes was interpreted as resulting from the explosive ejection of the hot plasma up into the loop and the consequent reduction in density and emission measure. Attempts to model this effect by Li et al. (1997) were unsuccessful, however, and they concluded that the footpoint soft X-ray source may be nonthermal, excited by low-energy electrons. Subsequent attempts to find more examples of this impulsive soft X-ray emission in the SXT data set have also been unsuccessful to date.

RHESSI's high sensitivity to soft X-ray emission down to ~3 keV with the shutters out of the field of view and its ability to do high resolution imaging spectroscopy over a broad energy range make it ideal for exploring this issue further. The X-ray images from the Soft X-ray Imager (SXI) on the next GOES spacecraft (activated in January 2003) will add immeasurably to our ability to determine the thermal energy during most flares when the RHESSI shutters are moved automatically into the field of view to avoid pulse pile-up problems. Thus, we expect to be able to make significant progress in the near future on the flare energetics issue. At present, we can say that the early RHESSI results have shown that the electron spectrum extends down to at least 10 keV in many flares. Thus, the total energy in accelerated electrons has to be an even greater fraction of the total flare energy than was previously thought. We can conclude that this component is at least as energetic as the energy in the soft X-ray emitting plasma and may be an order of magnitude or more higher in some flares.

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